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SPONTANEOUS AND PILOTED IGNITION OF PINE NEEDLES

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ABSTRACT

*Spontaneous and piloted ignition of ponderosa pine (*Pinus ponderosa *Laws.) needles were investigated in an isothermal atmosphere. Four levels of sample moisture content were tested and minimum heat flux intensities required to produce ignition, times to ignition, and surface temperatures at time of ignition were recorded. Piloted ignition occurred at lower flux intensities and in less time than did spontaneous ignition. A significant difference in delay time to ignition was found to exist for sample moisture contents above 7.7 percent.*

OXFORD: 431.5

KEYWORDS: forest fuel ignition, ignition, pilot ignition, spontaneous ignition, pine needle ignition

Many workers have studied the ignition and pyrolysis of cellulosic materials (Thomas and others 1958; Simms 1960, 1961, 1963; Martin 1963; Akita 1959; Koohyar and others 1968; Wesson and others 1971), but their research has not furnished needed information about ignition of forest fuels. Fine forest fuels--needles, leaves, twigs, grass, and lichens--are primarily responsible for the spread of forest fires. Ignition temperatures of these fuels are necessary if the rate of fire spread is to be accurately predicted by such fire-spread models as that advanced by Rothermel (1972). The relationship of ignitability of forest fuels to their physical properties, proposed by Anderson (1970), must also be verified by experimental data before it can be used reliably to appraise the fire potential of forest fuels.

Ponderosa pine (*Pinus ponderosa* Laws.) needles are an important fine forest fuel in the Western United States. Cast needles greatly influence the rate of fire spread on the ground and form a needle drape in the living tree that contributes greatly to fire crowning.

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A study of ignition properties of fine forest fuels undertaken at the Northern Forest Fire Laboratory pointed up this need for more specific information on pine needles. The results of this portion of the study are reported in this paper.

OBJECTIVES AND PROCEDURES

The objective of this study of pine needles was to measure (1) the time required for ignition to occur, and (2) the surface temperature at the onset of ignition. The Stockstad-Lory ignition furnace (Stockstad and Lory 1970; Stockstad 1972, 1973) was used for all testing. Both spontaneous and piloted ignition were studied using 1- by 0.076-inch needle sections.

The sample temperature was measured by a 3-mil platinum versus platinum 10-percent rhodium thermocouple placed on the forward end of the sample. The ignition chamber temperature was measured by a similar thermocouple in the immediate vicinity of the sample thermocouple (Stockstad 1972). Both thermocouples were connected to a recorder and their output plotted against time.

Uniform maximum-diameter sample size was obtained by passing pine needles through a 0.076-inch "go-no-go" gage. Uniform sample length was obtained by cutting sections from needles of desired diameter with a miniature saw driven by a modified high-speed hand tool.

All samples were kept at ambient air temperature of 22° to 24°C prior to testing. Time required for a sample to exhibit stages of glowing or flaming ignition was recorded. Sample temperature was also recorded during this period. The temperature at the time of exothermic reaction or flaming was defined as the ignition temperature.

Four levels of moisture content (4.9, 7.7, 12.5, and 33.1 percent) were studied. Moisture contents were obtained by placing test sections in conditioning cabinets containing saturated salt solutions (Schuette 1965). Twenty replications were made at each moisture level for both spontaneous and piloted ignition at every furnace temperature used.

Moisture content determinations were made on an ovendry weight basis by using both the conventional ovendry method and the vacuum ovendry method. In both methods, dry weight was subtracted from the original weight to give the weight of water present in the original sample. This figure was then used to calculate the moisture percentage.

The minimum furnace temperature used in the testing program was that at which no ignitions were observed in 20 trials at each moisture content. Furnace temperature was then raised 5° to 10°C and another series of 20 tests observed. This procedure was repeated until a furnace temperature was reached at which 100 percent of the samples ignited.

Several points on the thermocouple traces from a spontaneous ignition test were considered in the analysis (fig. 1). The point at which the sample temperature trace crossed and exceeded the ignition chamber trace was considered to be the beginning of the exothermic reaction. The second significant change in the sample trace was the point where the exothermic reaction increased in intensity resulting in an abrupt rise in the temperature of the sample. This point was considered to be the time and temperature at which the spontaneous ignition process would continue to the end result--visible glowing. An event marker activated by the test operator indicated the time and temperature at which visible glowing was observed. Tests indicated that operator reaction time was approximately one-half second; so this correction was subsequently applied to determine actual glowing ignition time and temperatures.

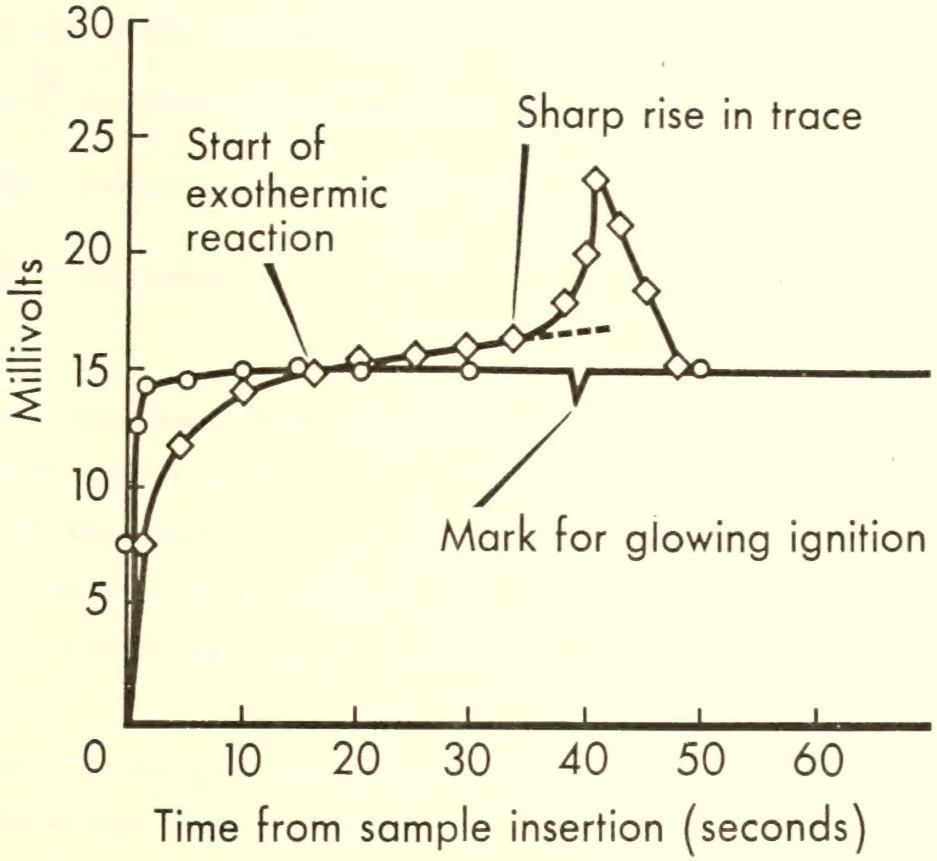

Figure 1.--Sample (◊) and ignition chamber (o) thermocouple traces from a spontaneous ignition test of a 1- by 0.076-inch section of ponderosa pine needle.

Pilot ignition tests were conducted in the same manner as spontaneous ignition tests, except for the introduction of a pilot flame (Stockstad 1972). Pilot ignition usually occurred at temperatures below actual furnace temperature; therefore, the beginning of the exothermic reaction, if one occurred, was not determinable by the previously described criteria. The point at which flaming ignition took place was marked by an abrupt, nearly vertical rise in the trace. An operator-activated event marker was not necessary for the pilot ignition testing.

PREDICTION OF HEATING RATES

Calculations were made to determine the heat transfer coefficients existing in the furnace during heating of the pine needle sections. Heating curves were calculated for three representative furnace temperatures, 360°, 390°, and 425°C. Values from these curves were later used to determine the total heat flux necessary to produce ignition. The assumption was made that the pine needle section would possess properties similar to those of a cylinder in parallel flow. Based on this assumption, the chart plotted by Giedt (1957) was used to obtain values for the Fourier number needed in the calculations.

Formulas used in the calculations were:

$$\theta = \frac{t_o - t_f}{t_i - t_f} = \text{a dimensionless temperature ratio} \quad (1)$$

$$N_{Fo} = \frac{\alpha\tau}{r_1^2} = \text{Fourier number} \quad (2)$$

$$N_{Bi} = \frac{K}{hr_1} = \text{Biot number} \quad (3)$$

where

t_o = sample temperature, °F at time t

t_f = furnace temperature, °F

t_i = ambient temperature, °F

τ = time from insertion of sample

$h = h_r + h_c$ = total heat flux for furnace at any given temperature

where

h_r = radiant flux and h_c = convective flux

r_1 = radius of pine needle = 0.038 inch

K = thermal conductivity of pine needle = 2.01×10^{-5} Btu/s-ft, °F (Byram 1952)

α = thermal diffusivity of pine needle = 1.73×10^{-6} ft^2/h, which was calculated from:

$$\alpha = \frac{K}{\rho C_p}$$

where

ρ = 35.6 lb/ft^3 (Brown 1970)

C_p = 3.27×10^{-1} Btu/lb (Byram 1952).

Assuming various sample temperatures between 38° and 424°C and furnace temperatures of 360°, 390°, and 425°C, τ was calculated and resulting values were tabulated in appendix table 1. The values for the 390°C furnace temperature are plotted in figure 2. The curve resulting from the actual heating of a needle section is also plotted in this figure.

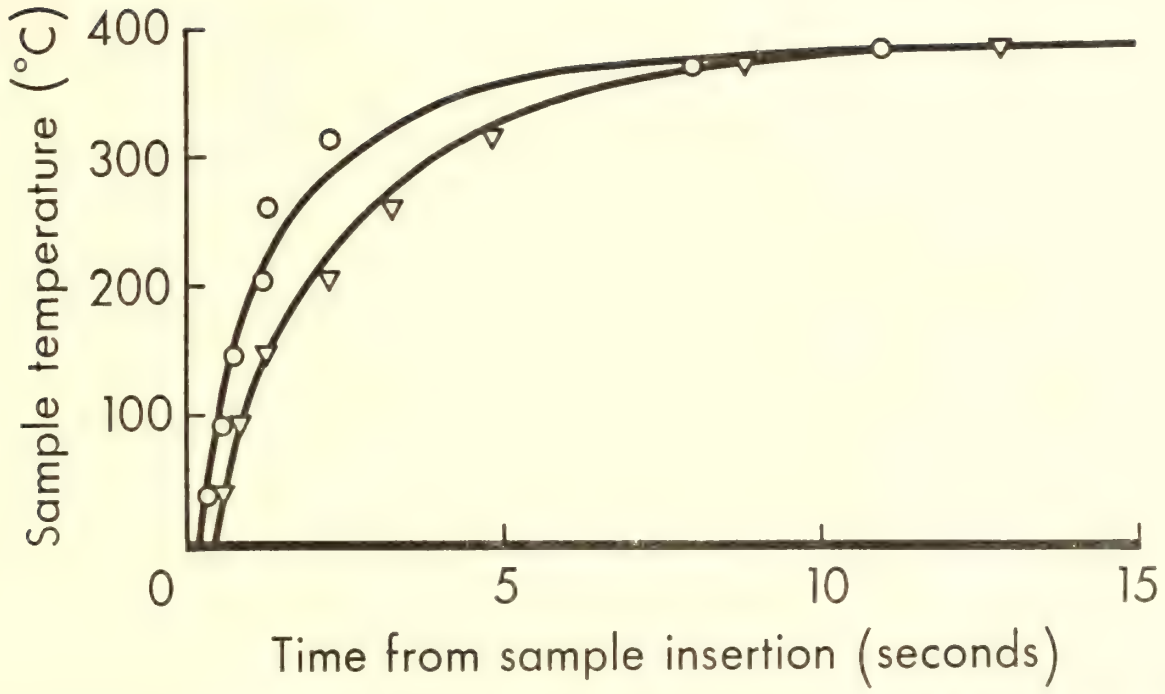

Figure 2.--Calculated (Δ) and actual (o) time-temperature history of a 1- by [illegible]-section of ponderosa pine needle at moisture content of [illegible] percent during spontaneous ignition at a furnace temperature of 390°C.

In all cases, the actual heating rate was faster than the calculated rate. A possible explanation could be the increase in absorption of radiant heat flux by the needle section as the needle darkened during the heating process. The heating of organic substances undergoing thermal decomposition is not a simple thermodynamic process; consequently, the use of a single Fourier number may not be applicable as it is for a metal cylinder. It seems likely that minor exothermic processes might begin relatively early as the sample is being heated, thereby contributing to a temperature rise more rapid than would be expected for inorganic materials. The use of a single value for the heat transfer coefficient existing at a given furnace temperature would also account for some of the disparities between the curves.

RESULTS

The results of the 720 spontaneous ignition tests and the 880 pilot ignition tests are given in appendix tables 2 through [illegible].

The minimum furnace temperature at which spontaneous ignition occurred was 365°C. A furnace temperature of 390°C was needed to produce spontaneous ignition at all moisture contents tested. A furnace temperature increase of 10°C from 380° to 390°C increases the probability of ignition from considerably less than 50 to 100 percent.

Figure 3 shows the relationship between the time required for the ignition processes to occur and the moisture contents tested at 390°C, the temperature at which 100 percent ignitions were first obtained.

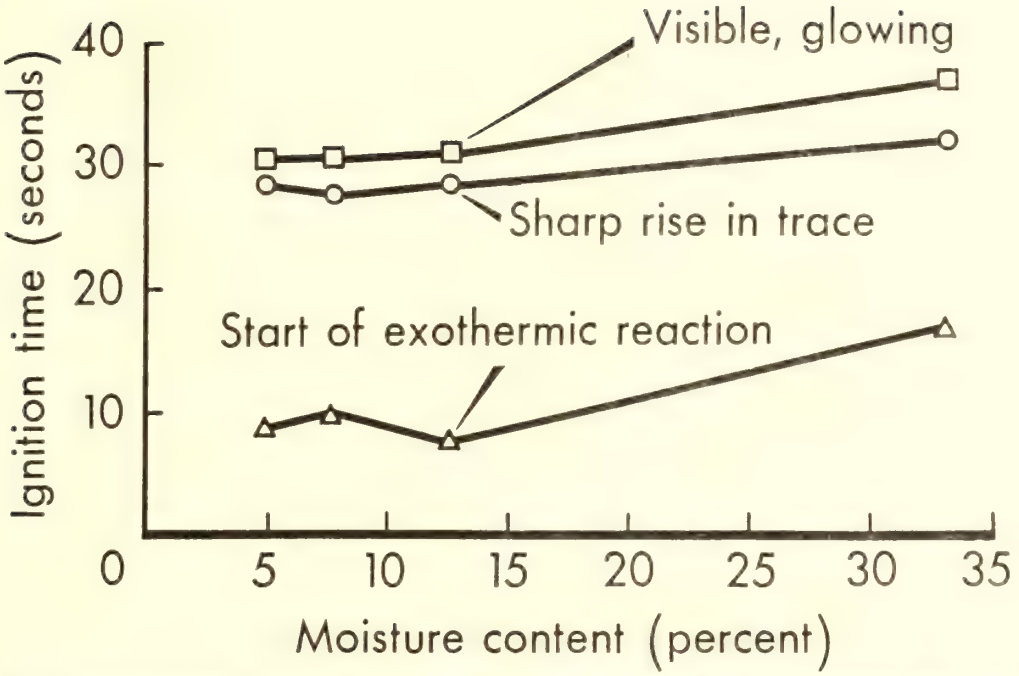

Figure 3.--Ignition time versus moisture content for spontaneous ignition of pine wall sections at a furnace temperature of 390°C.

Analysis of variance showed a significant difference at the 95 percent level of confidence in the times to glowing ignition at the 425° and 480°C furnace temperatures for the fuel moisture contents examined. Further statistical examination using Tukey's multiple range test showed a significant difference in time to ignition between all fuel moisture contents tested, with the exception of the relationship of 4.9 and 7.7 percent moisture contents.

Analysis of variance at the 95 percent level of confidence did not show a significant difference in ignition temperatures obtained for the fuel moisture contents examined.

The minimum furnace temperature at which pilot ignition occurred was 280°C. A furnace temperature of 350°C was needed to produce pilot ignition at all moisture contents tested. The increase in percent of ignitions per each 10°C change in furnace temperature was more gradual than was observed for spontaneous ignition. However, the big increase in ignition percentage still fell within a 30°C temperature range.

Figure 4 shows the average time required for ignition to occur at various furnace temperatures for the four fuel moisture contents tested. Figure 5 shows the relationship between the time required for ignition to occur and the various moisture contents tested at 350°C, the temperature at which 100 percent ignition occurred. Tukey's test indicated a significant difference in time to ignition existed at the 95 percent probability level for all fuel moistures tested above the 7.7 percent level.

Analysis of variance at the 95 percent level of confidence did not show a significant difference in the ignition temperatures obtained.

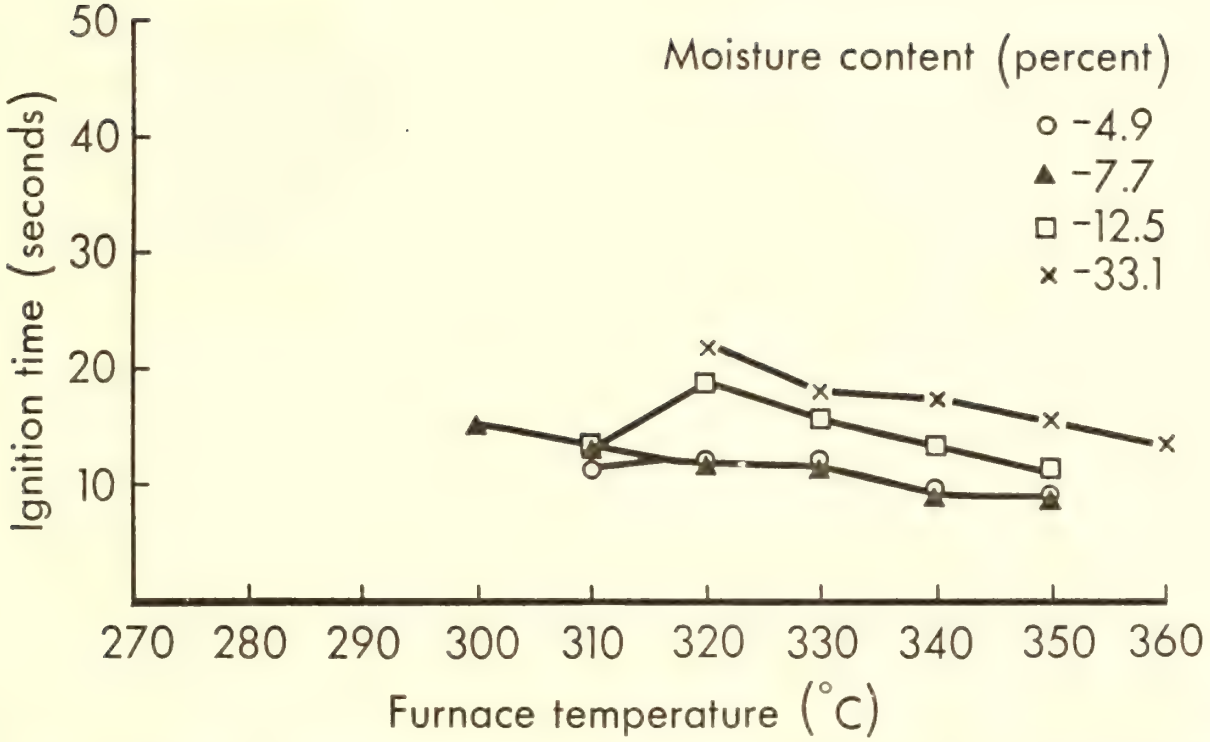

Figure 4.--Ignition time versus furnace temperature for pilot ignition of pine needle sections for various moisture contents.

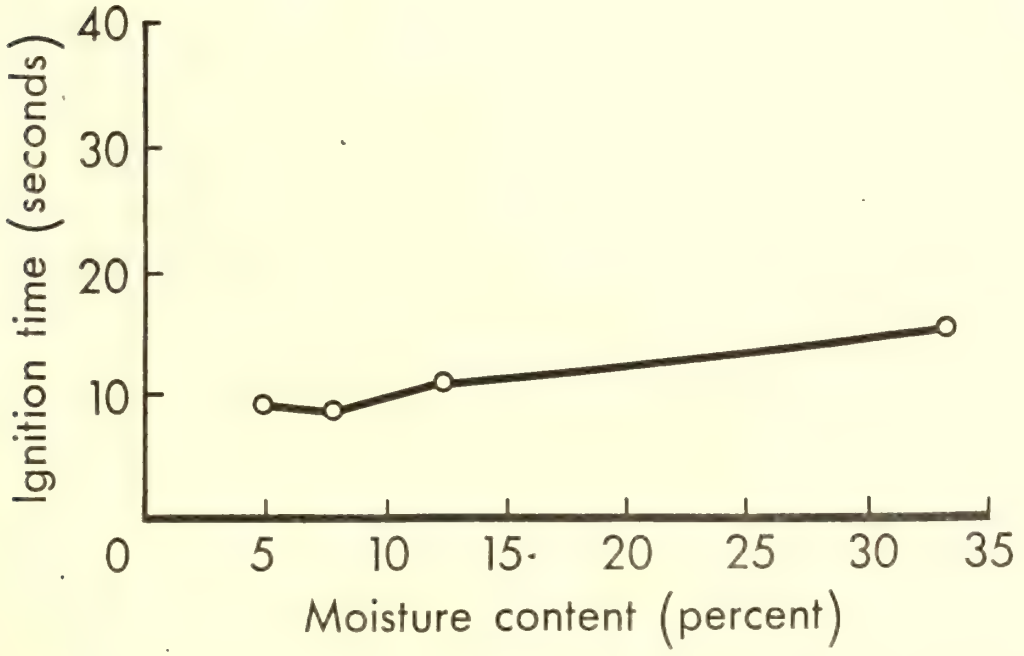

Figure 5.--Ignition time versus moisture content for pilot ignition of pine needle sections at a furnace temperature of 340°C.

DISCUSSION OF RESULTS

The total heat transfer coefficient for furnace temperatures of 375° to 390°C for each sample moisture content was calculated and is tabulated in appendix table 8. The average temperature for each 20 tests at which the exothermic reaction was considered to begin is also listed. From these values, an average heat transfer coefficient and exothermic temperature were determined. The total heat flux needed to produce spontaneous ignition at all moisture contents tested was then calculated to be 6.9 cal/cm^2 or a total of 29.8 calories. By using this value, an average ignition delay time of 13.6 seconds was calculated. The actual average ignition delay time was also 13.6 seconds.

The total heat flux necessary to produce ignition if a pilot flame is present is altered considerably. The total heat transfer coefficient for furnace temperatures of 320° to 350°C for each sample moisture content was calculated and is listed in appendix table 9. Also listed in this table is the average temperature for each 20 tests at which flaming ignition occurred. The average heat transfer and ignition temperature were then determined. The total heat flux necessary to produce flaming ignition was calculated to be 5.1 cal/cm^2, or a total of 19.9 calories. The average ignition delay time was calculated to be 13.3 seconds, compared to an actual average ignition delay time of 13.3 seconds.

Spontaneous ignition occurred at a minimum flux intensity of 0.49 cal/cm^2-s, although 0.53 cal/cm^2-s was necessary before ignition took place at all moisture contents tested. Pilot ignition occurred at a minimum flux intensity of 0.32 cal/cm^2-s; 100 percent of all samples tested ignited at intensities of 0.47 cal/cm^2-s.

CONCLUSIONS

Based on the obtained results, certain general conclusions can be drawn concerni ignition of pine needles when heated to ignition in an isothermal atmosphere. In the absence of a pilot flame, spontaneous ignition will occur at moisture contents up to 33 percent if the igniting agent is capable of producing a heat flux intensity of 0.53 cal/cm^2-s for 13.6 seconds. In the presence of a pilot flame, ignition will occur at moisture contents up to 33 percent if the igniting agent is capable of producing a heat flux intensity of 0.47 cal/cm^2-s for a period of 13.3 seconds.

A significant difference at the 95 percent level of confidence in delay time to ignition was shown to exist for both pilot and spontaneous ignition for needle moisture contents above 7.7 percent. No significant difference at the 95 percent level of confidence was found for moisture contents below the 7.7 percent level. From this, we conclude that the probability of an ignition occurring does not increase at moisture levels below the 7.7 percent level, but does decrease at moisture contents above this level.

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Table 1.--*Calculated and actual time for a pine needle section to reach a given temperature for three furnace temperatures*

Needle section temperature (°C)	Furnace temperature					
	360°C		390°C		425°C	
	Calculated time	Actual time	Calculated time	Actual time	Calculated time	Actual time
	Seconds					
38	0.5	0.5	0.5	0.4	0.5	0.4
93	.9	.8	.9	.7	.6	.5
149	2.1	1.0	1.4	.8	1.0	.8
204	3.0	1.5	2.2	1.2	1.5	1.0
260	4.4	2.5	3.3	1.2	2.2	1.3
316	5.5	5.5	4.9	2.2	3.1	2.1
343	9.6	10.0	[1]/ --	--	--	--
371	--	--	8.9	8.0	4.7	4.2
385	--	--	12.9	11.0	--	--
399	--	--	--	--	6.2	6.0
413	--	--	--	--	8.0	8.0
424	--	--	--	--	10.8	11.0

[1]/ No measurements taken.

Table 2.--*Percentage of spontaneous ignitions of pine needle sections at selected furnace temperatures for 20 tests per moisture content*

Furnace temperature (°C)	Percent moisture content			
	4.9	7.7	12.5	33.1
360	0	0	0	0
365	0	5	5	5
370	0	10	0	0
375	15	10	45	30
380	20	45	20	25
385	80	80	70	75
390	100	100	100	100
425	100	100	100	100
480	100	100	100	100

Table 3.--*Time to spontaneous ignition of pine needle sections at selected furnace temperatures averaged for 20 tests per moisture content*

Furnace temperature (°C)	Start of exothermic reaction				Sharp rise in trace				Visual glowing			
	Percent moisture content				Percent moisture content				Percent moisture content			
	4.9	7.7	12.5	33.1	4.9	7.7	12.5	33.1	4.9	7.7	12.5	33.1
	Seconds											
360	1/ --	--	--	--	--	--	--	--	--	--	--	--
365	--	18.0	15.0	21.0	--	57.5	33.5	59.5	--	65.7	38.0	66.0
370	--	18.8	--	--	--	51.8	--	--	--	61.4	--	--
375	15.0	13.0	12.4	18.6	41.0	40.2	40.2	46.9	41.2	45.0	44.1	59.2
380	17.4	16.7	17.5	18.8	46.4	43.1	48.2	41.8	49.4	49.2	52.4	54.1
385	9.4	8.6	8.8	20.3	29.2	22.5	29.6	40.5	31.0	25.9	34.2	44.4
390	8.4	8.8	7.6	17.0	28.7	27.9	28.6	32.1	30.4	30.6	31.0	37.1
425	8.5	8.2	6.9	14.8	15.7	15.7	12.5	17.5	18.1	17.6	14.6	20.1
480	9.1	7.1	8.0	11.7	9.8	8.2	8.6	12.3	11.0	9.5	9.9	13.5

1/ Dashed lines indicate no ignition occurred.

Table 4.--*Temperatures (°C) at time of spontaneous ignition of pine needle sections averaged for 20 tests per furnace temperature and varying moisture contents*

Furnace temperature	Start of exothermic reaction				Sharp rise in trace				Visual glowing			
	Percent moisture content				Percent moisture content				Percent moisture content			
	4.9	7.7	12.5	33.1	4.9	7.7	12.5	33.1	4.9	7.7	12.5	33.1
360	1/ --	--	--	--	--	--	--	--	--	--	--	--
365	--	367	367	361	--	391	396	391	--	426	432	428
370	--	367	--	--	--	384	--	--	--	404	--	--
375	371	372	369	368	393	402	402	402	404	426	422	422
380	378	378	380	379	400	399	409	404	414	421	434	410
385	388	387	382	384	408	421	401	407	430	463	429	428
390	379	378	373	382	407	412	403	401	427	441	425	432
425	403	406	404	420	435	438	435	441	485	482	474	497
480	468	466	467	467	479	478	479	481	548	534	547	562

1/ Dashed lines indicate no ignition occurred.

Table 5.--*Percentage of pilot ignitions of pine needle sections for selected furnace temperatures averaged for 20 tests per moisture content*

Furnace temperatures (°C)	Percent moisture contents			
	4.9	7.7	12.5	33.1
270	0	0	0	0
280	0	10	0	0
290	5	0	0	0
300	0	10	0	0
310	5	10	10	0
320	35	45	15	10
330	85	75	70	45
340	85	100	80	85
350	100	100	100	100
360	100	100	100	100
425	100	100	100	100

Table 6.--*Time to pilot ignition of pine needle sections for selected furnace temperatures averaged for 20 tests per moisture content*

Furnace temperature (°C)	Percent moisture contents			
	4.9	7.7	12.5	33.1
	Seconds			
	1/			
270	--	--	--	--
280	--	7.8	--	--
290	3.6	--	--	--
300	--	15.0	--	--
310	11.8	13.4	13.4	--
320	12.0	11.7	18.4	21.8
330	11.4	11.4	15.4	18.0
340	9.1	9.1	13.1	17.3
350	9.1	8.9	11.1	15.3
360	--	--	--	13.4
425	4.8	4.6	6.6	8.5

1/ Dashed lines indicate no ignition occurred.

Table 7.--*Temperatures (°C) at time of pilot ignition of pine needle sections at selected furnace temperatures averaged for 20 tests per moisture content*

Furnace temperature	Percent moisture contents			
	4.9	7.7	12.5	33.1
	1/			
270	--	--	--	--
280	--	251	--	--
290	259	--	--	--
300	--	237	--	--
310	243	251	238	--
320	270	264	263	285
330	291	289	298	303
340	296	292	306	324
350	303	310	313	323
360	--	--	--	325
425	330	319	341	351

1/ Dashed lines indicate no ignition occurred.

Table 8.--*Average heat transfer coefficient (h_t) and temperature at initiation of exothermic reaction during spontaneous ignition of pine needle sections for 20 tests per moisture content at selected furnace temperatures*

Furnace temperature (°C)	Sample moisture content	h_t	Start of exothermic reaction
	Percent	*Cal/cm²-°C*	*°C*
375	4.9	0.021	371
	7.7	.019	372
	12.5	.018	369
	33.1	.026	368
380	4.9	.025	378
	7.7	.024	378
	12.5	.025	380
	33.1	.027	379
385	4.9	.014	388
	7.7	.012	387
	12.5	.013	382
	33.1	.029	384
390	4.9	.012	379
	7.7	.013	376
	12.5	.011	373
	33.1	.025	382
Average of all tests:		.020	378

Table 9.--*Average heat transfer coefficient (h_t) and temperature at flaming ignition during pilot ignition of pine needle sections for 20 tests per moisture content at selected temperatures*

Furnace temperature (°C)	Sample moisture content	h_t	Flaming ignition
	Percent	*Cal/cm²-°C*	*°C*
320	4.9	0.015	270
	7.7	.015	264
	12.5	.023	263
	33.1	.027	285
330	4.9	.015	291
	7.7	.015	289
	12.5	.020	298
	33.1	.023	303
340	4.9	.012	296
	7.7	.012	292
	12.5	.017	306
	33.1	.023	324
350	4.9	.012	303
	7.7	.012	310
	12.5	.015	313
	33.1	.020	323
Average of all tests:		.017	296

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